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THE SPACE SHUTTLE AS AN ELEMENT IN THE NATIONAL SPACE PROGRAM

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10. ABSTRACT

An examination of the economic justification and potential funding problems of the space transportation system (STS) recommended for development by the President's Space Task Group in September 1969. The concept of a two-stage, fully reusable launch vehicle that can place a 40,000 to 50,000-lb payload into low earth polar orbit is currently being studied by the DOD and NASA for possible inclusion in future STS programs. Based on traffic rates derived from conservative options in the STG and DOD space plans, this shuttle, with an estimated RDT&E cost on the order of $9 billion, could show a net transportation cost saving of $2.8 billion by 1990. However, shuttle development would require a peak civilian space budget in excess of $7 billion in 1975, about double the present level. Viewed over the long term, the shuttle has definite merit, but its immediate economic justification depends on the pace that is finally adopted for the national space program.

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PREFACE

In September 1969, the President's Space Task Group recommended that the Department of Defense and the National Aeronautics and Space Administration jointly develop a low-operating-cost space transportation system (STS), the principal element of which would be a two-stage, fully reusable, low-operating-cost earth-to-space shuttle. Although a space shuttle may make the transportation of men and materials into space more efficient, and may also reduce the cost per pound of payload in orbit, compared with present booster systems, many important questions remain unanswered:

1. What levels of space traffic are necessary to justify economically the development of a shuttle?
2. What should the size and operating characteristics of the shuttle be?
3. When should development start?
4. How would the shuttle help the Air Force and NASA realize their respective goals?
5. How will technological obsolescence affect operations, in view of the expected 20-year (or longer) operational lifetime of the STS?

This Memorandum concentrates on questions of economic justification and potential STS funding problems. It is believed that the economic issues discussed here will have important implications for future Air Force actions on the STS and on possible alternative booster programs.

This is an interim report of an STS study that is presently under way at Rand. Additional results will be published when the study is completed.

This Memorandum is an updated version of RM-6244-PR, which was published in April 1970. The original report was based on research completed in January 1970, before the fiscal 1971 budget was announced. Changes and modifications in the mission models and system concepts have occurred since the original report was prepared; the more significant of these have been incorporated in this revision. These changes,

however, do not affect the basic conclusions of the original report. Neither the original nor this updated version reflect the more recent changes in the DOD and NASA space budgets.

A talk based on the text of the original report was presented at the AIAA Advanced Space Transportation Meeting in Cocoa Beach, Florida, on February 5, 1970.

SUMMARY

The concept of a two-stage, fully reusable launch vehicle that can place a 50,000-lb payload into low earth orbit is currently being studied by the Department of Defense (DOD) and the National Aeronautics and Space Administration (NASA) for possible inclusion in a future space transportation system. Although such a vehicle has been recommended for development by the President's Space Task Group (STG), that development is not easy to justify. Based on traffic rates derived from conservative options in the STG and DOD space plans, this space shuttle, with an estimated RDT&E* cost of almost $9 billion, could show a net (undiscounted) transportation cost saving of $2.8 billion by 1990. However, shuttle development would require a peak civilian space budget in excess of $7.0 billion in 1975, about double the present level. Other annual funding levels, while not as large as the peak levels, still exceed current budgets by significant amounts. Alternative space plans might be adopted that would alleviate budget peaks by slipping various elements in the basic space plan (e.g., reduced shuttle operations), but none of those examined in this study resulted in savings in space transportation costs sufficient to compensate for the space shuttle's RDT&E and investment costs through 1990. Also, while a saving of $2.8 billion seems large, total program costs for a variety of plans range from about $75 billion to about $140 billion (1975 to 1990), and any program uncertainties could cancel these savings or make them appear small by the time they are predicted to be realized.

Some transportation cost savings might be augmented by redesigning satellites to use the excess payload potential of the shuttle, by employing the shuttle to recover and reuse satellites, or by using the shuttle for satellite maintenance in orbit. Very preliminary estimates have shown cost savings directly attributable to satellite redesign to be between $150 million and $200 million per year. These savings could strengthen the economic rationale for the shuttle.

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*Research, development, test, and engineering.

While primary emphasis has been placed on a shuttle with a 50,000-lb payload capability, preliminary cost estimates indicate that there is little difference in total space transportation costs through 1990 for design payload weights as low as 25,000 lb, as long as the cargo-bay volume remains at 15-ft diameter and 60-ft length. Furthermore, the funding peaks in the civilian space budget would not be reduced markedly by designing the space shuttle for a smaller payload weight. At the same time, considerations such as flexibility in satisfying unanticipated future requirements and the ability to realize promised satellite cost savings argue for the larger shuttle.

It appears that estimated costs for individual designs of generic shuttles having a given payload capability would not vary significantly, using presently available cost-estimating techniques. Also, the total space funding requirements over the next 20 years are not significantly different for plans that use the shuttle for space transportation and those that accomplish the same missions without the shuttle. All of these results indicate that criteria other than cost should be used to evaluate the desirability of the space transportation system.

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I. INTRODUCTION

Despite the recommendations of the President's Space Task Group (STG) for expeditious development of an earth-to-orbit shuttle system,[1] and the strong support of various governmental agencies for such a program,[2-4] the prospects for an operational space shuttle before 1980 are not bright. The long-range attractiveness of a low-recurring-cost reusable space transportation system (STS) whose prime element is the shuttle is widely acknowledged--many feel that such a system will be necessary to exploit the full potential of space. Nevertheless, the appropriateness of and justification for *immediate* shuttle development are being challenged on two principal grounds: (1) the development risks are too high, and (2) national funding priorities presently exclude a space program sufficiently large to warrant shuttle development.[5] Others question the depth and completeness of the favorable analyses advocating this development.[6]

We need not repeat the criticisms of shuttle development here. Instead, by reviewing the case for shuttle development, we shall illuminate some potential trouble areas. Since the most persuasive case for the shuttle derives from its supposed economic advantages, the bulk of our remarks will deal with funding of space programs and the effects of shuttle development and operation.

The STG, the Department of Defense (DOD), the National Aeronautics and Space Administration (NASA), the President's Scientific Advisory Council (PSAC), and many engineering and scientific organizations and societies (e.g., the AIAA[7]) have all identified the shuttle as an important element in a future national space program. In the time period since these reports were made public, support for their proposals within the administration and the Congress has not mounted noticeably, and both the administration and the Congress are now deeply immersed in reducing "nonessential" government spending. Space programs are particularly visible targets for cost reduction, and those that lack solid scientific worth or are unduly expensive are certain to be questioned. Still, strong pressures for maintaining current U.S. preeminence in manned space flight remain; many feel that Congress would act favorably

on a modest proposal to support a civilian space program, possibly at a dollar level somewhat less than one-half of one percent of the GNP per year, on the grounds that it would help basic scientific research, maintain a viable national technology base, contribute to national security, and build national pride and prestige.* Assuming the existence of a modestly funded manned-space-flight program, it remains to be determined whether a shuttle system should be developed to support this program.

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*See Refs. 8, 9, and 10 for arguments supporting this position.

II. IS THE SHUTTLE ECONOMICALLY ATTRACTIVE?

Could the RDT&E* costs of the shuttle be recovered within an acceptably short period of time? To address this question completely, the analyst must consider (1) estimated space traffic rates (hence, national space plans), (2) shuttle design (size, configuration, etc.), and (3) the availability of the requisite technology. This Memorandum will not address questions about technology or their relevance to the desirability and philosophy of shuttle development;** nor do we treat the important questions of which shuttle design or configuration is the most attractive. Further, we have restricted our attention to new two-stage launch vehicles that are fully reusable, LOX-LH_2 rocket-propelled, and have vertical-takeoff and horizontal land-landing capability, automatic self-checkout, and other desirable features that make routine shuttle launch and recovery operations conform more nearly to aircraft-like operations than to current launch-vehicle procedures. Our primary consideration is a shuttle having a 50,000-lb payload capacity and a 10,000-cu ft cargo bay; secondary consideration is given to shuttles having a cargo bay of the same volume but smaller design payloads.***

To estimate space traffic rates, we have used the STG National Space Plan Option III and DOD Space Plan B, a modest military space plan that emphasizes current, well-defined military support missions.(1) Because of the generally conservative traffic-rate estimates implied by these plans, this is a more severe test of the economic justification of the shuttle than would result from using the more ambitious plans found in the STG report.

For simplicity, in this study the shuttle will be regarded as economically desirable if after a specified period the total savings over other methods for accomplishing the *same total effort* exceed the costs of the shuttle's RDT&E and investment. (This very narrow definition

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*Research, development, test, and engineering.

**This topic is treated in Ref. 5.

***In this Memorandum, a 50,000-lb-payload shuttle is a shuttle that can place 50,000 lb of discretionary payload into a 100-n-mi-high circular polar orbit. Its payload capacity for other orbits varies, being as high as 80,000 lb at 100-n-mi-high circular orbits of 28.5-deg inclination.

will be expanded later.) Obviously, the total number of shuttle launches required during that period importantly affects the shuttle's desirability; heavy traffic favors the shuttle concept, while light traffic favors the use of current or new expendable launch systems. In estimating traffic rates from the various space programs defined by the STG and DOD, care must be taken to determine which payloads (and how many) can fit in the shuttle's cargo bay and how many launches are needed to support the various military, unmanned civilian, and manned NASA programs (scheduled crew rotations, space-station logistics, in-orbit propellant-transfer demands, etc.).

Given our tentative launch-traffic estimates (both DOD and NASA launches), an estimated cost for shuttle RDT&E plus facilities of $9.0 billion, an assumed 100-flight useful lifetime, and a two-week shuttle turnaround time, the money recovered by the shuttle would exceed its cost after about 11 years of operation (late in 1987).* The annual launch cost savings in the mid- and late 1980s would often exceed $1 billion per year. Ignoring other factors, our estimated traffic rates (about 60 launches per year in the mid-1980s) seem to justify initiation of shuttle development.** However, neither NASA nor DOD alone would have sufficient space traffic by 1990 to warrant separate shuttle developments.

The estimates of the shuttle's useful lifetime and its turnaround time were taken directly from the STG report.[1] Together, those estimates largely determine the total number of vehicles to be purchased over a specified time and therefore strongly influence conclusions about shuttle desirability. We have estimated a requirement for 10 shuttles (exclusive of the three vehicles required for test and evaluation) through 1990 to support the basic space plan. Were the vehicles never to crash, wear out, or become too obsolete to use, the space plan could be supported with only three shuttles, saving $3.3 billion in investment. Similarly, if turnaround times were doubled (four weeks rather than two), we would have to

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*In most cases, our conclusions are based on comparisons of the shuttle with current launch systems. When other launch systems are used as a comparison, we shall so note.

**In this preliminary study, we have generally not considered such economic factors as discount rates and inflation, although these will be important considerations in any final decision.

add three more vehicles, at an incremental cost of $1.3 billion. If the shuttle's useful lifetime were halved (50 flights rather than 100), six additional vehicles would be required, at a cost of $2.45 billion. The final decision to develop a fully reusable shuttle must, of course, reflect much more than a simple cost summary. For example, the space plan used to generate a traffic model should be analyzed carefully, since the average yearly expenditure required for it is larger than the current (and declining) space budget, and the amount by which its peak funding exceeds current funding levels is substantial. This latter peak, occurring as early as 1975, is particularly troublesome as it is caused primarily by the shuttle's development schedule. These points are discussed in more detail later in this Memorandum.

As well as we can estimate at this time,* the civilian space plan proposed by the STG cannot be implemented if the NASA budget is limited to $4 billion, or even $5 billion, per year (see the Appendix for a brief description of the major hardware items and their estimated costs). Excluding all consideration of a manned flight to Mars, a follow-on manned lunar exploration program, and a 50-man orbital space base, the joint funding of the shuttle and an earth-orbital space station could lead to a NASA budget in excess of $7 billion in 1975.**

Slippage of the shuttle's initial operational capability (IOC) date past that of the space station would help reduce these funding peaks. At the same time, such delays could seriously perturb current

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*Our current estimates are quite crude. At the completion of the ongoing NASA space-base studies, substantial improvements in these estimates should be possible. Nevertheless, we do not feel that this crudeness alters our principal results.

**The annual funding estimates developed at Rand and those in the STG report (for Option III) compare as follows:

	Costs ($ billions)		
	FY 1974	FY 1975	FY 1976
Rand estimate	6.4	7.1	6.7
STG estimate	5.0	5.4	5.5

These differences are almost entirely attributable to contrasting estimates of the shuttle's RDT&E costs, the STG estimate being only $5.0 billion, compared to our estimate of $9.0 billion, or possibly more.

space planning. Other hardware would have to be modified or developed to support crew rotations to and from the space station. If new expendable boosters were developed and the Apollo spacecraft modified, this hardware would then tend to encourage further delay in the shuttle's development schedule by weakening the uncertain case concerning the shuttle's economic advantages. Not only would there be a desire to exploit the new expendable boosters at least to the point of recovering their development costs (savings over current launch hardware), but also the existence of a new, cheaper-than-current launch system would increase the shuttle's break-even level of launching traffic, hence moving the break-even point further into the already uncertain future. Previous justifications for rapid shuttle development have hinged explicitly upon acceptance of the STG space plans, and hence on a large space funding peak in the mid-1970s. Thus, the case for shuttle development is still open.

If the shuttle is desirable economically but may not be funded because of annual budget limitations, then it is important to extend the analysis to include alternative space plans that may be more acceptable from a funding standpoint and to reassess shuttle cost benefits for these new plans.

III. IS THE SHUTTLE ECONOMICALLY DESIRABLE, GIVEN ALTERNATIVE SPACE PLANS?

To generate alternative space plans that still attempt to satisfy the objectives for U.S. activities in space described by the STG, we have modified the basic STG Option III by delaying, stretching, or eliminating various program elements in the basic plan (which we shall call Plan 1). These modifications suggest seven alternative plans (see Table 1): Plans 2, 3, and 4 aim at reducing NASA's mid-1970s funding problems, and Plans 5 through 8 represent attempts to reduce the overall space budget level by eliminating the lunar exploration program. Some plans achieve both goals, but only at the cost of decreasing the scope of the national space program. None are recommended as replacements for those in the STG report; rather, they serve as comparisons for the purposes of our analysis.

Table 1

ALTERNATIVE SPACE PLANS: IOC DATES FOR MAJOR PROGRAM ELEMENTS

Program Element	IOC Date							
	Plan 1	Plan 2	Plan 3	Plan 4	Plan 5	Plan 6	Plan 7	Plan 8
Space station	1977	1977	1981	1981	1977	1977	1981	1981
Space base	1984	1985	1987	1987	1984	1985	1987	1987
Lunar station	1981	1983	1983	1983	(a)	(a)	(a)	(a)
Lunar base	1983	1985	1985	1985	(a)	(a)	(a)	(a)
Shuttle	1977	1982	1977	1981	1977	1982	1977	1981
Nuclear ferry	1981	1983	1983	1983	(a)	(a)	(a)	(a)
Lunar tug	1983	1985	1985	1985	(a)	(a)	(a)	(a)

[a]Program eliminated.

In examining these alternatives, we shall focus on several closely related issues regarding the shuttle and its development:

1. At what level of the annual nonmilitary space budget is a space shuttle economically advantageous?
2. Should the shuttle and a space station be developed simultaneously, and if not, which should be given priority?

3. If the shuttle's IOC is delayed into the 1980s, how are the current civilian and military space plans affected? And should a new expendable launch vehicle be developed in the interim?

The remainder of this Memorandum will be concerned primarily with the first issue; the others are touched on only in passing. We have subdivided the alternative space plans into five interrelated programs:

1. A manned earth-orbital program consisting of a 12-man space station that grows to a 50-man base and scientific and experimental modules located near the station; the cost of supporting the station is included (along with the transportation costs).

2. A manned lunar exploration program consisting of a 6-man orbiting lunar station, a 6-man permanent lunar base, scientific modules for both the station and the base, and hardware to construct the lunar base; the transportation costs are included.

3. A program containing all the elements of the STS, including their RDT&E costs, investment costs, and support costs.

4. A residual program including all other (unmanned) civilian programs and overhead costs.

5. A military space program.

Table 2 lists the major elements of these programs and the Plan 1 schedules for each.

The breakdown in year-to-year total obligational authority (TOA) for the various programs is shown in Fig. 1. Costs for all of the unmanned portions of the basic space plan are taken directly from Refs. 1 and 3. We shall not vary these costs as we examine alternative plans, except as necessary because of changes in the STS, on the assumption that neither the scientific nor military programs will depend explicitly on the existence of the shuttle but will be funded on their own merits. We have arbitrarily placed the shuttle's entire RDT&E and investment costs under NASA's budget. This, of course,

Table 2

PLAN 1 SCHEDULE FOR PROGRAM-ELEMENT PROCUREMENT AND YEARLY SHUTTLE FLIGHTS

Item	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990
Number of Items To Be Procured														
Manned earth-orbital program														
Living module	1	0	0	0	1	0	2	0	0	0	0	0	0	0
Working module	1	0	0	0	1	0	3	3	0	0	0	0	0	0
Nuclear-power module	0	0	0	0	0	0	2	0	0	0	0	0	0	0
Manned lunar program														
Lunar-station module	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Lunar base	0	0	0	0	0	0	1	0	0	0	0	0	0	0
STS program														
Shuttle	2	0	1	0	1	1	1	0	1	0	1	1	0	1
Nuclear ferry	0	0	0	0	1	0	1	0	1	0	0	1	0	1
Lunar tug	0	0	0	0	0	0	1	0	0	1	0	1	0	0
Saturn V	0	0	0	0	2	0	2	2	0	2	0	2	0	2
Saturn V (downrated)	1	0	0	1	3	0	5	1	1	0	0	1	0	1
Orbital fuel depot	0	0	0	0	2	0	0	0	0	0	0	0	0	0
Number of Shuttle Flights														
NASA	14	9	10	12	36	34	42	41	39	40	39	39	46	46
Military	27	22	24	22	17	20	20	17	17	20	20	20	20	20

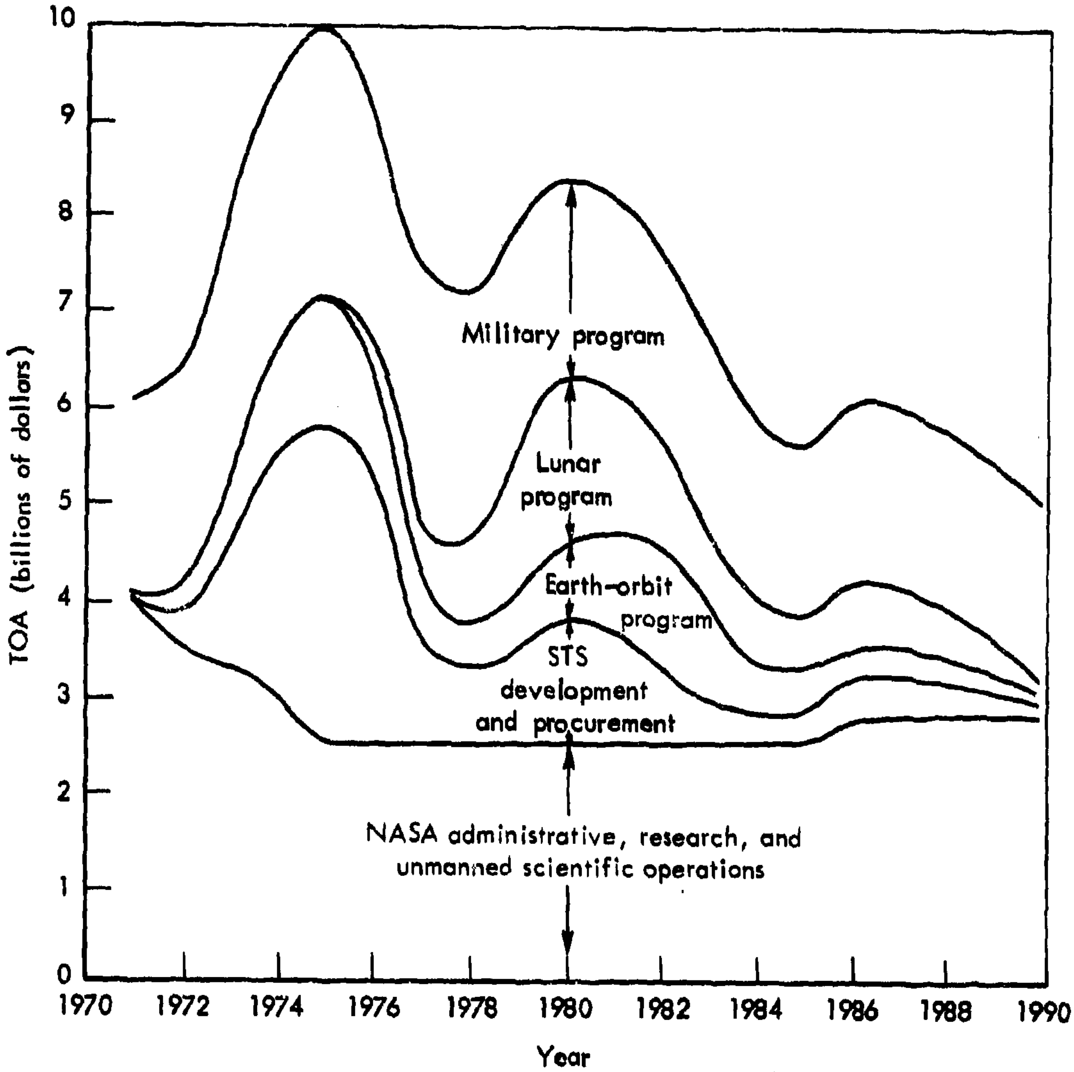

Fig. 1—Annual space-program TOA: base case (Plan 1)

accentuates NASA's budget problems while lessening those of the DOD.*

The previously mentioned NASA funding peak in 1975 is evident in Fig. 1, as is a somewhat lesser peak in 1981 (due to preparations for the lunar program and the space base). The cumulative space-plan costs through 1990 are estimated to be $141 billion, an average of $7.0 billion per year (an average NASA budget of $4.9 billion per year). Figure 2 compares annual NASA costs for Plans 1 through 4 (those plans that include a lunar program). The attempts to reduce the funding peak in the mid-1970s by delaying various program elements are seen to be effective, although a peak occurs between 1980 and 1982 for Plans 2 and 4 because of concurrent shuttle and lunar-program developments. Plan 3, in which the space station is delayed but not the shuttle, does not result in as great a decrease in the 1975 peak as do Plans 2 or 4, but it has no sharp peak in the early 1980s. The total costs of each space plan are shown in Table 3. The differences among the totals seem small.

Table 3

TOTAL COSTS THROUGH 1990 FOR PLANS 1 THROUGH 4

Plan	Costs ($ billions) NASA	NASA plus Military
1	97.6	141.4
2	97.4	142.7
3	94.6	138.4
4	94.9	139.0

*It might be suggested that the DOD provide funds for a portion of the shuttle development, on the basis that the shuttle is responsive to their transportation needs. One possibility would be for the DOD to pay a percentage of the total costs commensurate with its projected use rate. Another would have the DOD and NASA share the costs at the same ratio as their anticipated launch cost savings. Regardless of the total costs subsumed in the military budget, we will anticipate funding-peak problems, and, in fact, the burden might be shifted to two agencies rather than one.

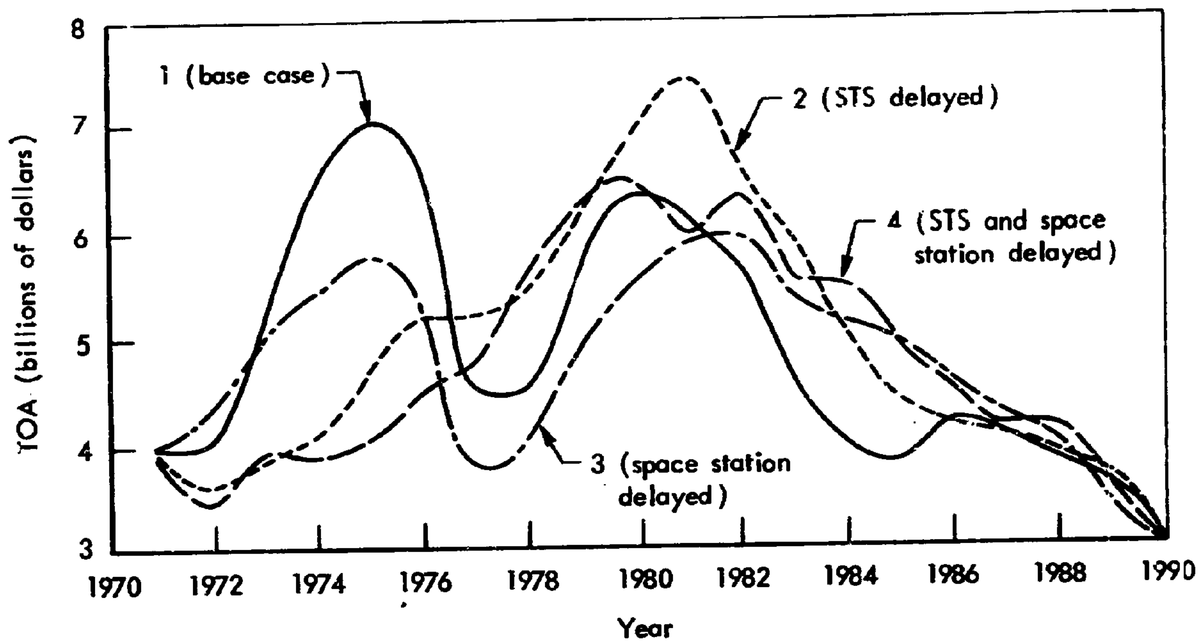

Fig.2—Annual NASA TOA for Plans 1 through 4

Figure 3 shows comparative year-by-year costs for Plans 5 through 8. (These plans are, in essence, Plans 1 through 4 without a lunar-program component.) The cost trends noted for Plans 1 through 4 also occur in these four plans, except that peaks caused by the lunar program in the early 1980s are reduced. The total cumulative costs are less than those for plans 1 through 4, as shown in Table 4.

Table 4

TOTAL COSTS THROUGH 1990 FOR PLANS 5 THROUGH 8

	Costs ($ billions)	
Plan	NASA	NASA plus Military
5	80.4	124.2
6	81.4	126.7
7	78.3	122.1
8	77.9	123.0

It is possible to consider each of these eight alternative plans without a shuttle, replacing it with Titan III and Saturn V derivatives and modified Apollo hardware where necessary. Ignoring the effects on space planning arising from funding considerations,* we have examined the cost differences that would result from removal of the shuttle in each plan. Figure 4 shows the cumulative savings or cost increases caused by development and use of the 50,000-lb-payload shuttle for each plan. In only the base case, Plan 1, does the shuttle demonstrate a net monetary gain by 1990, and even under this plan, the savings seem to be marginal. Unanticipated increases in the shuttle's RDT&E or operating costs would quickly deplete any savings indicated, and because of the basic uncertainty in our cost estimates, such increases cannot be ruled out.

*It might be noted that removing the shuttle program altogether diminishes most of the funding-peak problems mentioned above, i.e., if the shuttle is not developed, much of the pressure for delaying other programs would be relieved.

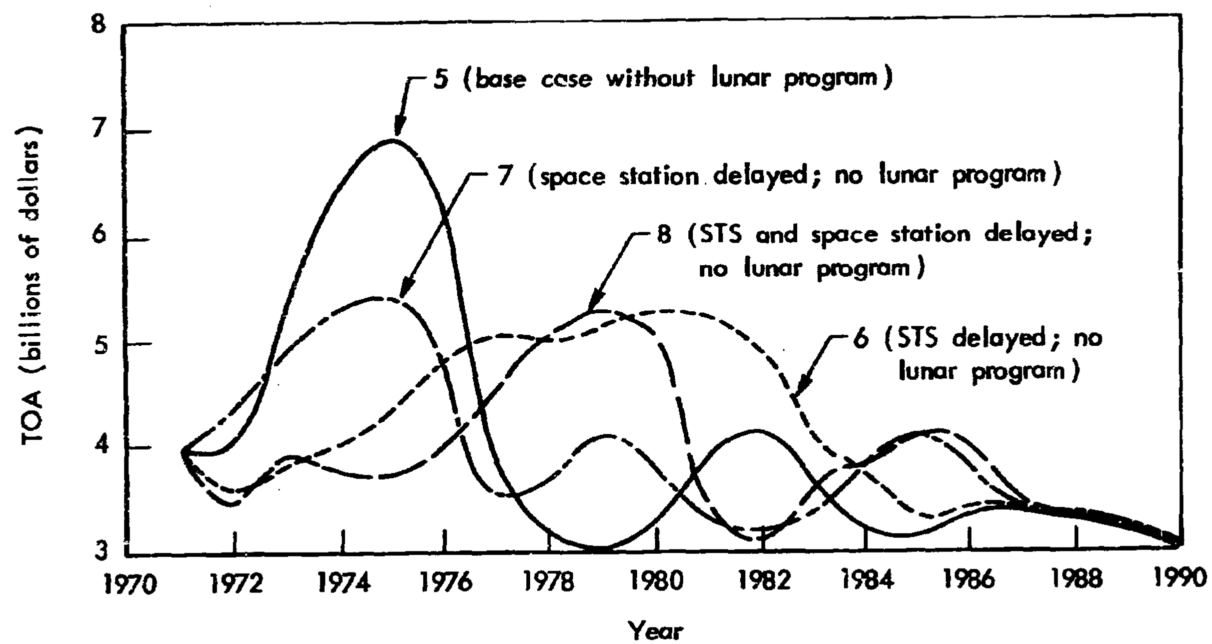

Fig.3—Annual NASA TOA for Plans 5 through 8
(no lunar program)

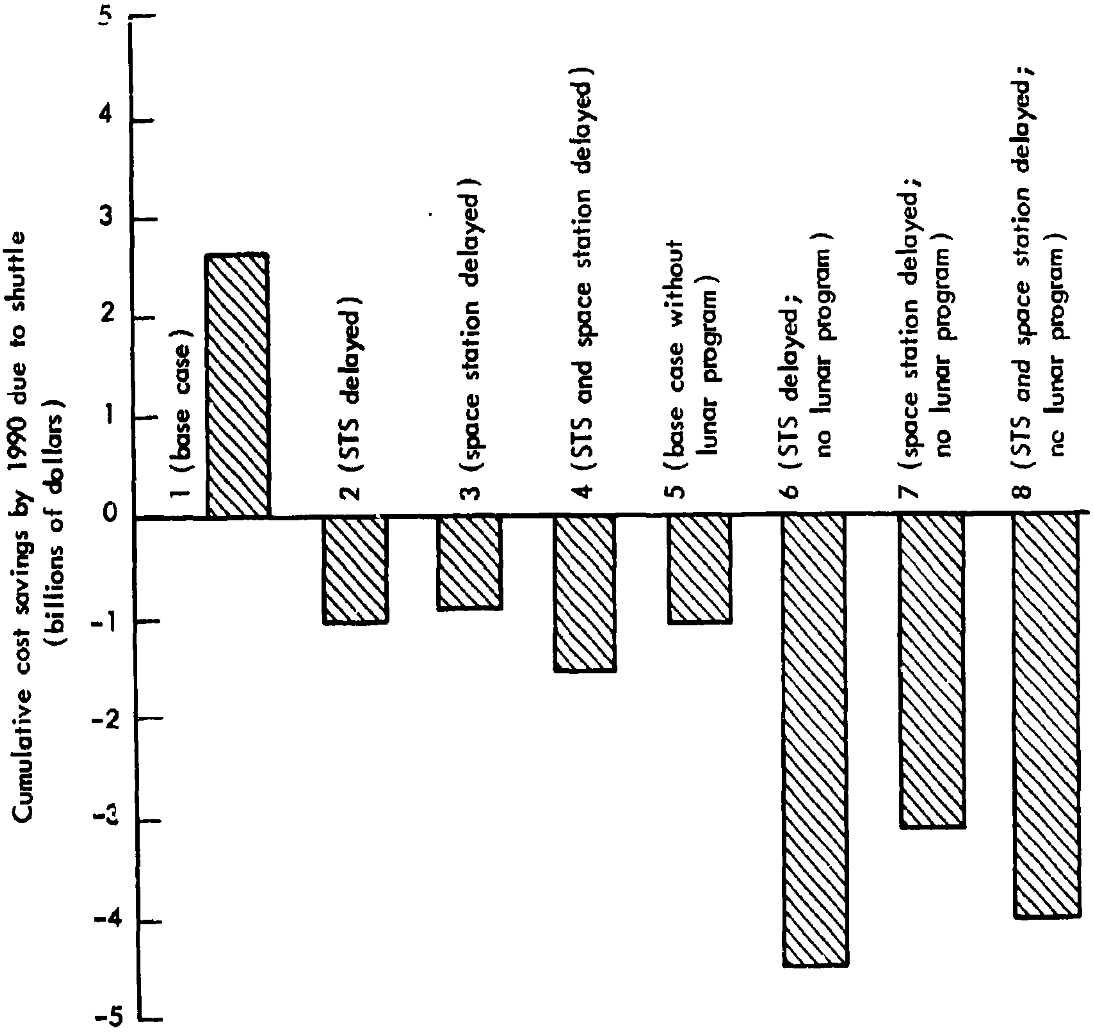

Fig.4—Effect of shuttle development and use on costs of alternative space plans
(shuttle payload = 50,000 lb)

If the entire STS were to be abandoned (i.e., the shuttle, the nuclear ferry, the lunar tug, the orbital fuel depots, and the orbit-to-orbit chemical shuttle for synchronous-orbit flights), the total costs to accommodate the projected space traffic through 1990, using the basic space plan, would be increased by $3 billion over the costs that would result if only the shuttle were abandoned. Since this cost differential appears after an operational lifetime of less than 10 years for the lunar-specific elements, a lunar program using existing hardware (modified as necessary) seems inefficient, i.e., the nuclear ferry is a worthwhile investment compared to employing existing hardware.

Even though there are apparent large differences in pace among Plans 1 through 4, their total costs through 1990 are nearly identical. Delaying various program elements within the plans does not produce a sharp decline in total expenditures; such delays only vary the years in which these expenditures occur. Clearly, different plans are not equivalent in their effects on U.S. manned-space-flight activities. Delaying the space station would affect many aspects of these activities; similarly, delaying the shuttle's IOC date past that of the space station would increase costs for both NASA (about $300 million per year for support of the 12-man station) and the DOD (about $150 million per year). We urge further study of the tradeoffs between funding-peak problems associated with concurrent shuttle and space-station development, the loss to U.S. manned-space-flight activities associated with funding the shuttle first, and the added yearly cost penalty (to both NASA and the DOD) associated with giving priority funding to the space station.

IV. WHAT IS A GOOD SIZE FOR THE SHUTTLE?

There continue to appear in the literature discussions about shuttle size selection. Protagonists for shuttles smaller than that recommended in the STG report argue that the decreased capability per launch would be compensated for by the decreased cost of development and procurement, and in addition might lessen development risks. We will test this assertion for shuttles sized to carry payloads between 25,000 and 50,000 lb by estimating their RDT&E, investment, and launch-operations costs through 1990.

The estimated RDT&E costs for a space-shuttle development program are shown in Fig. 5 as a function of design payload for a constant cargo-bay volume of 10,000 cu ft.* The costs do not vary directly with design payload; only modest RDT&E cost savings result from a large payload reduction. Total space-program transportation costs (through 1990) for Plan 1 (which includes the lunar program) and Plan 5 (no lunar program) are shown in Fig. 6 for space shuttles with design payloads of 25,000, 40,000, and 50,000 lb. Included in these costs are RDT&E, investment, and operational costs of an orbit-to-orbit shuttle.**

Several cost factors interact to make total transportation costs insensitive to design payload: (1) RDT&E costs decrease only slightly with decreasing design payload weight at a fixed payload volume; (2) reducing the design payload increases the number of shuttle flights for

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*Other studies (e.g., classified work by I. Rattinger, et al., Aerospace Corporation) have demonstrated that the ability of the space shuttle to support military, lunar, and interplanetary flights is drastically curtailed if the volume of the cargo bay is reduced significantly below this figure. However, total RDT&E costs appear to be a strong function of this bay size. Whether shuttles of smaller bay size are worth considering depends on the anticipated mission model, but preliminary investigations indicate that small-volume shuttles do not support the military and deep-space requirements sufficiently to amortize even the smaller RDT&E costs.

**The costs of Saturn and Titan launch vehicles required for launching NASA payloads that exceed either the volume or weight capabilities of the shuttle are not included in Fig. 6. Most of the large NASA hardware (e.g., space-station and space-base models) for earth-orbital and lunar missions are launched using the Saturn vehicles. In the case of the delayed IOC of the shuttle, Titan vehicles are used for operational resupply.

those missions the shuttle can support, thus increasing both operational and investment cost per mission; (3) smaller-payload shuttles cannot support all the project missions, forcing the use of expendable launch vehicles for some payloads; and (4) the orbit-to-orbit shuttle frequently cannot be recovered as shuttle design payloads are decreased, so an increasing number of orbit-to-orbit shuttles must be expended rather than recovered and reused. These cost advantages and disadvantages tend to cancel each other for the range of design payloads considered. Thus total cost provides little basis on which to choose between different shuttle sizes.

Several other factors influence the selection of a size of a shuttle. These include (1) annual funding problems; (2) future mission-model uncertainties; (3) obsolescence; and (4) uncertainties in current cost estimates. Although we have touched only on the first of these factors (and we note that the annual funding peaks for a 25,000-lb-payload shuttle would be nearly as great as those shown earlier for a 50,000-lb design), the other considerations would appear, on balance, to favor larger shuttles.

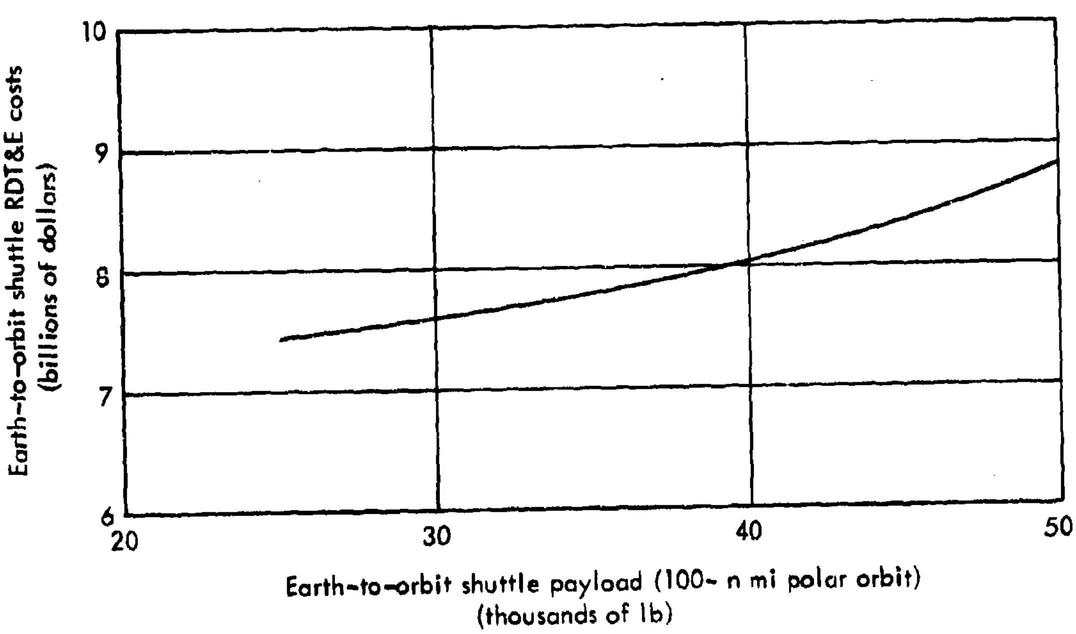

Fig.5—Earth-to-orbit shuttle RDT&E costs versus payload-weight capability

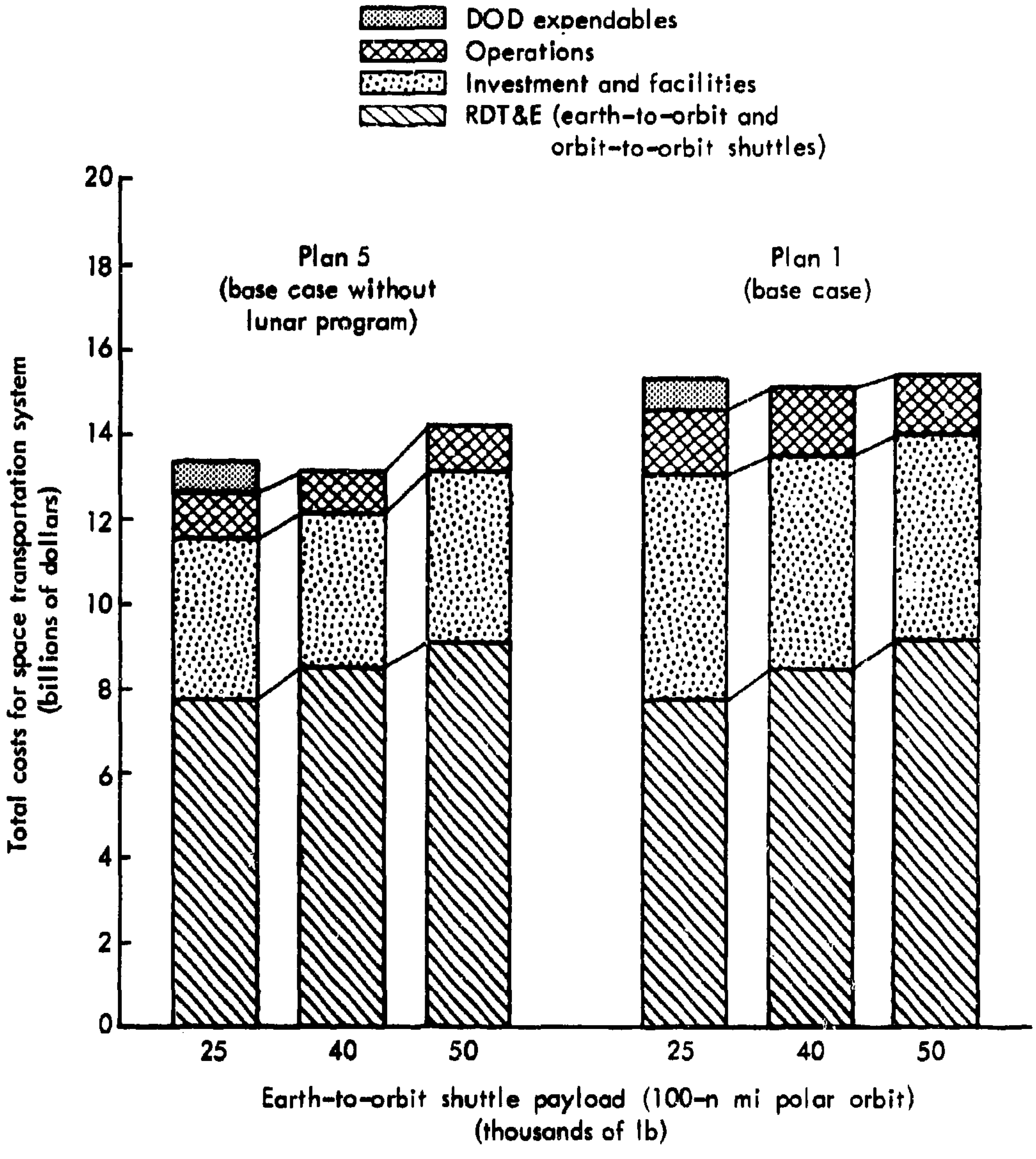

Fig.6—Total space transportation system costs to DOD and NASA versus earth-to-orbit shuttle payload weight capability (through 1990)

V. WILL SATELLITE COST SAVINGS JUSTIFY THE SHUTTLE?

Transportation cost savings are not the only benefits promised by the shuttle development. It is often asserted that the availability of a low-cost earth-orbital STS will produce significant savings in total space-system costs, over and above those directly associated with launch vehicles. Satellite R&D and hardware costs could probably be substantially reduced if satellites did not have to be designed to an irreducible minimum weight but could take advantage of the excess shuttle payload capacity. Recovery and reuse of satellites might pay a handsome cost dividend for certain satellite systems, while in-orbit maintenance might save money for others. The magnitude of these additional savings is often implied to be great, or at least sufficient to erase any nagging doubts about the desirability of the shuttle, but it has remained unquantified. Such savings are difficult to measure, but bounds can be crudely estimated.

In seeking an upper bound to payload cost savings, we ask, "How much money, in theory, is invested in satellite programs whose cost will be affected by the existence of a low-launch-cost shuttle, and what fraction of this investment can be recovered by changes in satellite design or system operation?" In practice, only a moderate portion of the entire space budget will be influenced by the development of the shuttle (ignoring launch costs and procedures). Some space programs, particularly those involving manned space flight, are already designed to take advantage of the shuttle. Other missions, such as placing hydrogen fuel in orbit for nuclear ferry flights to the moon, are simply not subject to cost-benefit tradeoffs. Still, many unmanned satellites, mainly military, mostly modest in volume and weight, are theoretically subject to design or operational changes resulting from reduced launch and recovery costs per payload. For the military and civilian space programs mentioned above, which might be benefited by the shuttle, we have tentatively *estimated* the total costs to be between \$1.5 billion and \$2.0 billion per year.

Were all these costs recoverable, or nearly recoverable, the shuttle would quickly pay for its R&D costs, and few would question its

worth. However, ignoring satellite recovery and reuse, the savings resulting from redesigning satellites are likely to be less than the reductions in launch costs,* which we estimate to be between $300 million and $400 million per year. Assuming that each shuttle flight costs on the average only one-tenth as much as a current launch operation, we estimate total satellite cost savings of between $150 million and $200 million per year. These savings are not negligible; nor are they stupendous. Figure 7 shows the sum of transportation and satellite cost savings for Plans 1, 4, and 5, using the lower of these two bounds.

Potential satellite cost savings do affect shuttle selection and the development schedule. Smaller shuttles offer less potential than large shuttles for realizing satellite-redesign cost savings. In fact, many future payloads that require synchronous orbits already approach the equivalent of a 25,000-lb low-earth-orbit requirement; thus the possibility of satellite redesign being affected by the lower launch costs of a smaller shuttle is already doubtful. Also, most satellite systems involved are likely to be funded, whether or not a shuttle is developed. Thus programs calling for early shuttle development are favored.

We have said little about potential cost savings arising from recovery, reuse, or in-orbit maintenance of satellites. Such savings probably affect a smaller percentage of the total budget than do those from satellite redesign, but a higher fraction of the former may be actually recoverable. No inclusive estimates of cost savings from

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*This tentative conclusion was reached by Carl Builder, of Rand, in a theoretical analysis of the relative savings resulting from a new low-cost booster and redesigned satellites. He discovered that if satellite design were assumed to be optimized for current high-cost boosters and then reoptimized to make use of a new low-cost shuttle, it would be possible to estimate the total savings without detailed design knowledge. For example, if the launch costs are reduced by 90 percent, two-thirds of the total savings will be the result of differences in launch costs, and only one-third will be due to satellite savings.

It is possible that future systems using current launch hardware would not be optimally designed, for whatever reasons present systems are not minimum-cost. The existence of a shuttle could have a catalytic effect, spurring changes in present satellite design and management practices. In that case, the shuttle could produce cost savings larger than those indicated by present studies.

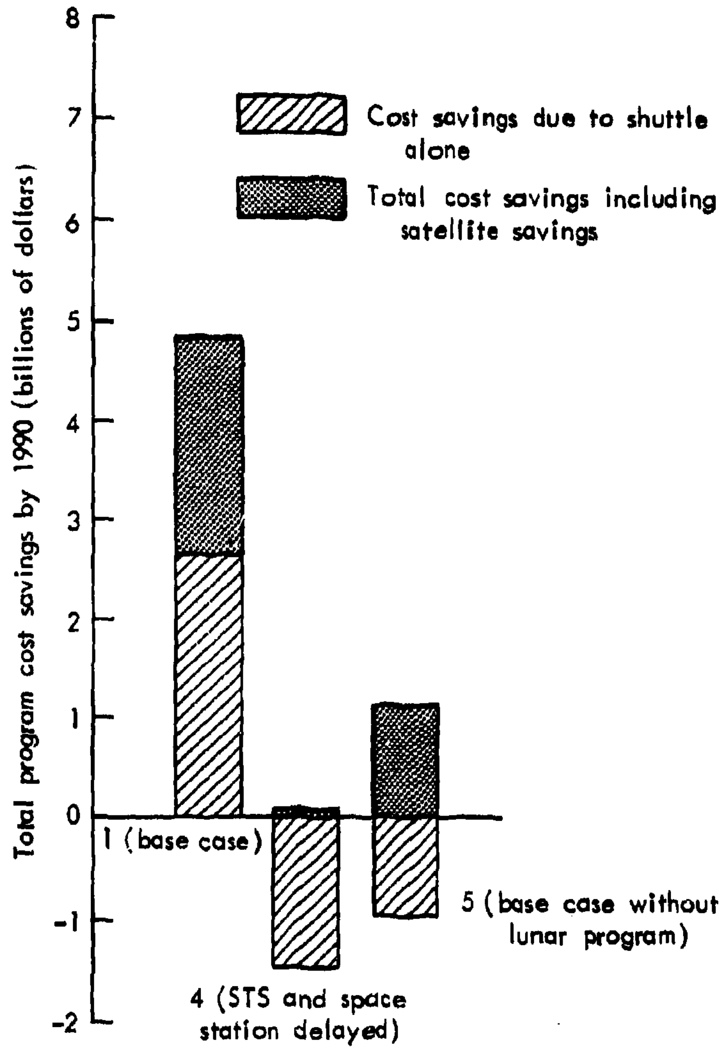

Fig. 7—Effect of satellite savings on total cost savings of Plans 1, 4, and 5

(shuttle payload = 50,000 lb)

satellite recovery, reuse, and in-orbit maintenance exist, but as an order-of-magnitude estimate, we place them at about equal to those from satellite redesign. We also note that the two satellite cost savings are not directly additive. The same satellite systems are involved in both, and the two options are competitive methods for reducing system costs.

VI. OTHER CONSIDERATIONS

If either total transportation cost savings nor total satellite cost savings are sufficient to justify the shuttle's large RDT&E expense, it is still possible that other attributes of the shuttle might trip the decision in favor of it.[(11)] Most of these attributes involve convenience of operation or an enhanced use of space. We shall not discuss convenience here; however, arguments about the increased use of space imply a major impact on the space program and deserve further consideration.

It seems inevitable that low-cost transportation to earth orbit will open up space to an extent that cannot be fully anticipated. If space transportation resembles other transportation systems, in effect, the impact of low-cost space transportation may be difficult to overestimate. But how low does this cost have to be for space to be fully exploitable? Surely, space transportation systems have a long way to go before they will be available to the general public. Tourism, for example, would require that recurring costs be reduced by at least an order of magnitude below those attributed to the shuttle.[(12)] Moreover, it does not seem likely that commercial entrepreneurs will become involved in space in the next 20 years, although there is some disagreement on this point.[(13)]

What, then, are the space activities that present shuttle designs are supposed to engender? Probably not scientific missions. Some space-exploitation missions, e.g., communications or navigation, might be created, but the biggest impact of the shuttle will probably be in the military domain. Military missions that have unique capabilities when performed from space have already been identified and, where justified, acted upon. There are other missions, however, that have ground-based competitors, and the cost-effectiveness of these missions will undoubtedly be sensitive to launch-vehicle costs.*

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*An enhanced use of space could increase the total costs of the space program. It is assumed in this discussion that other, nonspace costs could be reduced by an even greater margin, thus showing a net gain for the country as a whole.

Some space systems that lack ground-based counterparts have not received serious consideration for funding simply because they are too expensive. Some of these programs (usually experimental feasibility investigations) would clearly benefit from low-cost transportation. As has been true in many similar nonspace enterprises, promising but nonessential programs might be funded if they were inexpensive, in the hope that the additional expenditures would produce a useful system. The ultimate worth of untried programs is impossible to estimate; only direct experience is likely to help.

This brief discussion by no means settles the question of whether or not new mission potentials justify a shuttle development. Some new space programs would likely be funded once a shuttle became operational, and no doubt, some of these would turn out to be very worthwhile. To attempt to justify the shuttle on this basis would, however, be risky--a gamble on an uncertain future.

VII. OBSERVATIONS AND CONCLUSIONS

The space shuttle promises many future advantages, including cost savings, if the STG schedule for an orbiting space station, space base, and lunar programs can be implemented. However, serious funding difficulties exist that may force rescheduling of the STG programs, in which case near-term development of the currently proposed two-stage fully reusable shuttle may or may not be desirable. Viewed over the long term, the shuttle has definite merit, but its immediate economic justification depends on the pace that is finally adopted for the national space program.

Our studies to date have produced these tentative observations:

1. Cost considerations provide little basis for selecting an optimum shuttle size; on the other hand, flexibility in meeting unanticipated launch requirements, potential for satellite cost savings, and growth potential favor a larger rather than a smaller shuttle.
2. Cumulated over a time period of 20 years, the differences between total space funding requirements for shuttle-supported and no-shuttle plans are insignificant. This may suggest that cost criteria should be regarded as secondary in the evaluation of shuttle desirability.
3. The STG schedules calling for shuttle IOC by 1977 should be studied further. Such an IOC date at once raises two concerns: Is present technology adequate to plan on only a five-year R&D and procurement program (from 1972 to 1977)? And could adequate funding be obtained to support such a program within so short a time span, while the program itself remains subject to question?
4. A shuttle system appears most advantageous with an early IOC date and heavy expected space traffic. However, early IOC dates cause *large, near-term* funding peaks. While these peaks can in some measure be reduced through judicious rescheduling of the various space-program elements, the amount of early funding required and the need for immediate program start are

still formidable problems. Furthermore, any significant delay in the shuttle's IOC date will seriously reduce whatever economic advantage the shuttle has over competing, nonreusable systems.

Finally, it may be that the proper way to take a longer view of a new STS is to consider it as the first in a long line of reusable launch systems, leading eventually to a truly low-cost, high-utility system. It is possible that within 50 years, space will be frequented by vacationers, tourists, and industrial manufacturing concerns, as a result of launch systems descended from the first reusable shuttle. At some time the urge to start toward that goal will be great enough to warrant the development of a reusable STS. The principal question is whether that time is now.

Appendix

HARDWARE DESCRIPTIONS

To compare the budgets of the proposed alternative space plans over the next 20 years, it is necessary to consider the costs of the various hardware items required in each plan. The items considered are *representative* of the types that would be required but are not necessarily those currently being studied by NASA, nor are they necessarily the elements that NASA would actually procure for a given plan. General descriptions of the major hardware items and their development and production costs are given below.

SPACE SHUTTLE

The space shuttle represents a unique type of vehicle. There are no previous historical data upon which its development and production costs can be based; therefore, analogs of current hardware cost data and estimating relationships have been applied.

Assumptions about applicable estimating relationships have been made by breaking the space shuttle into appropriate components for which there are available data. The major-component breakdown and the relevant data base are as follows:

1. Structure: high-speed aircraft
2. Propulsion: liquid-rocket and turbojet engines
3. Subsystems: manned-spacecraft components, primarily non-structural, such as avionics, environmental control systems (ECS), electrical power, etc.
4. Thermal protection: high-temperature materials

The gross weight and estimated costs of the 50,000- and 25,000-lb-payload shuttles are given in Table A-1. Estimated costs for the 40,000-lb-payload shuttle were obtained by interpolation between the 25,000- and 50,000-lb-payload shuttles.

Table A-1

ESTIMATED COSTS FOR VARYING PAYLOAD CAPABILITY
($ Millions)

Payload (lb) (polar launch)	RDT&E	Facilities	First Unit[b]	Launch Operations[a]	
				Fixed	Recurring
50,000	8,735	250	436	1.0	2.52
40,000	8,100	250	385	1.0	2.22
25,000	7,400	250	342	0.9	1.97

[a]The fixed launch-operations costs include propellant, launch control and recovery, program integration, command and control facility, equipment maintenance, etc. First-flight recurring costs are based on 0.75 percent of first-unit shuttle costs less spares and AGE for refurbishment, and were arbitrarily selected to follow a 90 percent cumulative-average log-linear learning curve.

[b]First-unit costs are following ground- and flight-test articles. These costs include spares and AGE at 30 percent. Other numbers of units can be estimated by using a 95 percent cumulative-average log-linear learning curve.

SPACE STATION AND BASE

We have assumed that the space station and base would be built from common modules that would require the development of only three unique modular forms. The complete 50-man base would consist of the following modules: maneuvering, zero-g, artificial g, nuclear power, hub, hangar, warehouse, hospital, living quarters, and assorted booms and fairings.

The core, zero-g, warehouse, hospital, and living-quarters modules have been assumed, for the most part, to be common and have been designated the A Module, for estimating purposes. The hub and hangar modules have been assumed common and designated the B Module. The third module, the nuclear-power module, is unique and has no commonality with the other two. Development costs are related to the three forms of modules, although there are functional differences among them all. The assumptions on commonality were based on similar form, structural weight, and subsystems (reaction control, electrical power, communications, ECS, and crew stations and controls).

The components of the large space base would be grouped in eight A Modules, four B Modules, and two nuclear-power modules. The initial small space station (12 men) would require only one A Module and one B Module. Weights and costs of space-station and base components are given in Tables A-2 and A-3, respectively. The modules of the space

Table A-2

WEIGHTS OF SPACE-STATION COMPONENTS

Subsystem	Weight (lb)		
	A Module	B Module	Nuclear-Power Module
Structure	64,000	45,700	47,200
Adapter	2,600	2,600	...
Electrical power	6,000	2,750	4,700
ECS	9,000	3,000	...
Communications	2,110	1,100	...
Stability & control	170	...	...
Navigation & guidance	1,500	...	...
Crew system & display	8,260	2,000	...
Shielding	...	...	100,000
Electrical power (nuclear only)	...	...	26,450

Table A-3

COSTS OF SPACE-STATION COMPONENTS

Module	Cost ($ millions)		
	Development	First Unit	Launch Operations
A Module	2,500	190	90
B Module	1,065	96	53
Nuclear-power	250	70	0

station and base would be equipped for experiments to be performed in earth and lunar orbit and at the base. First-unit cost for equipped experimental and scientific modules would be from $120 million to $160 million.

LUNAR STATION AND BASE

Two modules would be used for the lunar station and one for the lunar base. The station, which is to be capable of housing 12 men, would consist of a living module and a zero-g module; the lunar base, also to be capable of housing 12 men, would be a single module. Because there are major differences between the station and the base,

additional development cost is incurred for the latter, although other costs are common to both station and base. Weights and costs of lunar-station and base components are shown in Tables A-4 and A-5, respectively.

The construction module that would be used to build the lunar base has a gross weight of 10,000 lb, a development cost of $75 million, and a first-unit cost of $25 million.

A lunar-descent stage would also be required to place payload on the moon (the lunar base, the construction module, etc.). This stage would have a gross weight of 150,000 lb, a development cost of $380 million, and a first-unit cost of $16 million.

Table A-4

WEIGHTS OF LUNAR-STATION AND BASE COMPONENTS

Subsystem	Weight (lb) Zero-g Module	Living Module	Lunar-Base Module
Structure	40,000	40,000	40,000
Adapter	2,600	2,600	2,600
Electrical power	14,000	14,000	16,000
ECS	5,000	5,000	7,500
Communications	650	200	650
Stability & control	200	200	0
Navigation & guidance	1,000	0	0
RCS	900	900	0
Crew system & display	3,000	5,000	3,000

Table A-5

COSTS OF LUNAR-STATION AND BASE

Item	Cost ($ millions) Development	First Unit[a]	Launch Operations[a]
Lunar station	2,800	190	90
Lunar base	1,400		

[a]Costs are common to station and base.

SPACE BOOSTERS

For those periods when the shuttle is not in use or when payloads are of such volume or weight that the shuttle cannot accommodate them, we have assumed that several boosters would be employed, including the Saturn V (SIC, SII, SIVB, and IU), Saturn VD (SIC, SII, and IU), Titan III-D, and Titan III-M.* Costs for the first units of these boosters procured after development are given in Table A-6. (The costs used in this study reflect the learning-curve effects of these prior units.)

Table A-6

COSTS OF SPACE BOOSTERS

Booster	Cost ($ millions) First Unit	Cost ($ millions) Launch Operations
Saturn V	215	40
Saturn VD	185	25
Titan III-D	31	(a)
Titan III-M	26	(a)

[a]Costs included in hardware.

SIX-MAN APOLLO SPACECRAFT

For those alternative space plans in which the shuttle operation would be delayed or in which there would be no shuttle, a six-man modified Apollo spacecraft would be used. This vehicle would have a gross weight of 20,000 lb, a development cost of $1 billion, a first-unit cost of $300 million, and a launch-operations cost of $73 million.

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*The Titan III-D and Titan III-M are uprated versions of the Titan III-C.

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